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ABSTRACT

District heating is a well-established system for providing energy efficient space and domestic hot water heating in dwellings in particularly in temperate and cold climate zones. Research has shown that going from the current 3rd generation district heating (3GDH) systems towards 4th generation district heating (4GDH) systems can facilitate a better integration between energy sectors, reduce grid losses and assist the integration of renewable energy sources. This article investigates the economic and energy effects of going from 3GDH to 4GDH for the specific case of Aalborg Municipality, Denmark based on overall hourly energy systems simulations. The analyses include effects from changes in excess heat potentials, changes in grid losses, and changes in efficiencies of conversion units in the district heating. Altogether, the analyses of the Aalborg case reveal that going from 3GDH to 4GDH decreases the primary energy consumption of the entire energy system by around 4.5% and the costs of the system by 2.7%.

1. Introduction

Several studies have found that district heating (DH) has an increased role to play in the future [1] – and also as part of 100% renewable energy sources (RES)-based energy systems [2,3]. For instance, DH provides a meaningful outlet for the inevitable losses from the production of electrofuels [4] and provides access to heat sources that are otherwise not appropriate in single-house applications, such as geothermal energy, and excess heat from industry, power stations, and waste incineration [5,6]. Likewise, DH gives access to low-cost energy storage systems [7], and can provide a flexible integration between the electricity and heating sectors by flexible use of e.g. cogeneration of heat and power (CHP) units, electric boilers and heat pumps (HP) [6,8].

Current 3GDH temperature levels are typically in excess of 80 °C giving cause to grid losses typically in excess of 20%. At the same time, the temperature levels of 3GDH limits the possibilities of utilising excess heat from thermal processes and causes suboptimal efficiencies in heat generation units including HP and CHP plants.

4GDH systems [9] are designed to facilitate the integration between sectors, reduce grid losses, and assist the integration of RES by working at lower temperatures.

Previous studies have already demonstrated this at a general national energy system level, such as [10,11] that both made holistic energy system analyses of the effects of 4GDH on future renewable Danish energy systems. However, where national investigations have used holistic energy system approaches, research using specific case studies to analyse the effects of 4GDH have focused on the direct effects on the DH system. This can be seen in works, such as, Ianakiev et al. [12] that investigate a DH scheme in Nottingham with forward temperatures at around 50–60 °C. Averfalk and Werner [13] creates a generic DH system based on climate conditions of Central Europe to estimate the effects on the DH price of different technologies in 3GDH and 4GDH.

Pakere et al. [14] investigate the effects of 4GDH on a DH system in a parish in eastern Latvia. Sameti and Haghighat [15] analyse the effects of 4GDH for a small area of seven buildings, which they compare with individual heating solutions. Volkova et al. [16]

Abbreviations: 3GDH, 3rd generation district heating; 4GDH, 4th generation district heating; COP, Coefficient of performance; CHP, Combined heat and power; DH, District heating; HP, Heat pump; PV, Photo Voltaic; RES, Renewable energy source.

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propose a methodology for transitioning to 4GDH and analyse the effects of 4GDH for the case of Tallinn in Estonia.

Also Kleinertz et al. [17] look into transitions to 4GDH systems, however, from a more narrow DH perspective and focusing amongst others on temperature levels in grids and storages. Ziemele et al. [18] present analyses of a DH system's conversion to biomass CHP. Askeland et al. [19] investigate the effects of a transition towards 4GDH in Norway finding positive effects on primary energy demand – but little effect on Norway's ability to provide flexibility for the rest of Europe.

Thus looking into the body of literature, there is a group of work on overall energy system analyses focusing on the integration of 4GDH into future smart RES-based energy systems – and analyses focusing on more detailed aspects of the transition, including temperature levels in DH systems, grid losses and DH production technologies.

The novelty of this paper is that it bridges the gap between the holistic national analyses with high shares of RES and the DH-focused case study analyses. Bridging this gap is important as it can provide a more detailed understanding of the effects of the transition to 4GDH on the entire energy system locally, where some of these aspects can be lost in more generalised national energy system analyses, and local case studies focusing on the DH system does not show the synergy effects that is expected to be important in future energy systems based on RES [20]. As such, in this paper the effects on the entire energy system of going from a 3GDH system to a 4GDH system in a RES-based energy system are investigated using a specific case.

Part of the investigation is to analyse the effects on the production units, where HPs in DH systems are particularly susceptible to temperature levels, where a lowered forward temperature results in higher thermodynamic efficiency. Previous analyses have demonstrated how going below the temperature levels required for domestic hot water heating and simply going for the minimum required for floor-heating can result in very high COP values [21,22]. However, this could require substantial retrofitting in terms of residential domestic hot water temperature booster technology as well as potentially changing radiators to floor heating.

A more conservative application of 4GDH is simply to approach the level at which no temperature boosting of domestic hot water is required, as suggested by Ref. [11]. Where 3GDH thus typically has forward temperatures around 80 °C, a 4GDH forward temperature in the 55 °C–65 °C range is thus a relatively conservative level at which retrofitting is minimised, and benefits are still harvested. In this paper 4GDH temperature levels are defined as 55 °C for the forward temperature and 25 °C for the return temperature, which have shown to be sufficient for providing comfortable temperatures as well as being legionella-safe with the proper installations in the individual buildings [10].

The specific case used in this paper is Aalborg Municipality in Denmark, where a 3GDH system has been operating for decades. The analyses focus on three elements where 4GDH has an advantage over 3GDH:

- Reduction in grid losses due to a lower temperature difference between the heat medium and surrounding soil.
- Improved possibility of utilising excess heat from industrial and service-sector processes either directly or indirectly through HPs.
- Effects on the production and storage technologies located at the DH plants.

The effects of the changes are simulated in the hourly energy systems analysis model EnergyPLAN.

In the next section, EnergyPLAN is presented in further detail, followed by case and scenario descriptions in Section 3. Next results from the energy systems analyses are presented and discussed, followed by the conclusion in Section 5.

2. Energy systems analyses using EnergyPLAN

EnergyPLAN is a priority list energy system analysis tool, that hourly simulates the energy balance of all energy sectors for a leap-year. It has a particular focus on the integration between sectors and the exploitation of sources of flexibility for the integration of variable RES. Working aggregated, groups of technologies are combined in one representation in EnergyPLAN; all onshore wind turbines are represented by one installed capacity and one hourly time series, for instance [23].

DH is categorized in three groups in EnergyPLAN depending on supply technology; systems based on boilers only; systems based on back-pressure mode CHP plants and systems based on extraction mode CHP plants. Other supplies may also be assigned to the three separate groups including for instance HPs, industrial excess heat and heat from waste incineration [23].

EnergyPLAN calculates the total annual cost for the entire modelled energy system, where investments are annualised based on stated lifetimes and an interest rate [23]. In this paper an interest rate of 3% is used to annualise the investment costs.

The tool is based on what the creators label "analytical programming" where all situations are handled according to a context-specific prescribed approach [24]. An overview of the fuels, technologies, and energy sectors that can be included in EnergyPLAN is shown in Fig. 1.

EnergyPLAN is useable for supernational, national, regional, and local (incl. municipalities) scale energy system analysis, and has been used in a high number of journal articles [25]. EnergyPLAN has previously been used for the simulation of municipal or town energy systems in Aalborg [26], Frederikshavn [27], Sønderborg [28], Bornholm [29] (all four in Denmark), Corinaldo [30], Bressanone-Brixen [31] (both in Italy), Gran Canaria [32], and Zagreb [33]. Likewise, EnergyPLAN has been used in studies evaluating the energy system effects of going from 3GDH to 4GDH in a national context [10,11].

3. Case and scenario description

This section introduces the Aalborg energy system including scenario data and potential 4GDH system benefits in terms of production and storage side benefits, changed DH grid losses, and change in exploitable excess heat sources.

3.1. Aalborg Municipality and its energy system

Aalborg Municipality is the third most populous municipality in Denmark with a population of 213,558 with 114,194 living in the city of Aalborg at the end of 2018 and fifth largest in terms of area at 1,137 km^2 [34]. The municipality has long-term goals of going towards 100% RES in the energy system.

The municipality has an extensive DH grid serving not only the main contiguous city more or less fully, but also links to DH systems in surrounding towns. A few towns within the municipality have separate DH systems based on gas CHP and biomass boilers [35].

In 2016, the industries in Aalborg Municipality used 2.35 TWh coal, 0.92 TWh biomass, 0.42 TWh natural gas, and 0.1 TWh oil. Aalborg is home to the largest energy consumer in Denmark, the cement factory Aalborg Portland. Through extensive heat recovery, this factory supplies a large share of the DH demand in the municipality. In 2016, a total of 1,176 TJ (0.33 TWh) was recovered for usage in the contiguous DH system in Aalborg, accounting for about

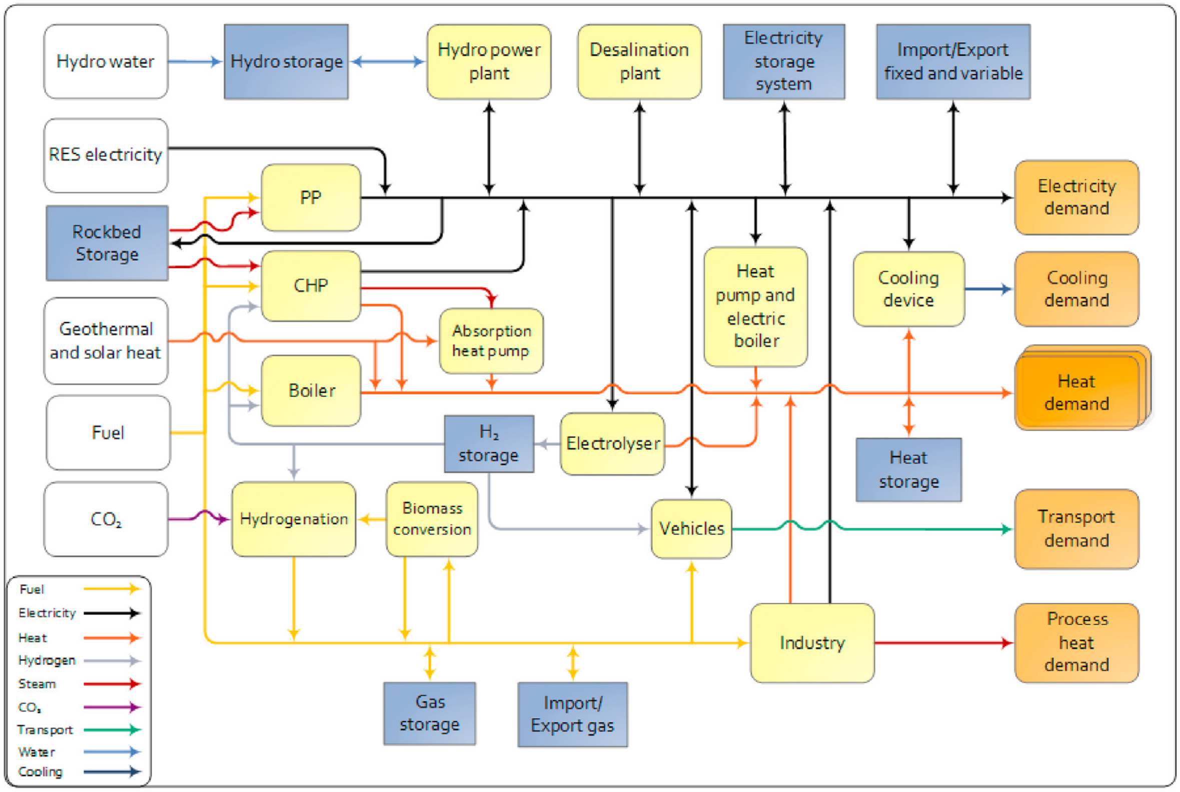

Fig. 1. Overview of EnergyPLAN v14.2 [23].

18% of the total DH production there. The remaining DH was mainly delivered by the local coal-fired CHP plant *Nordjyllandsværket* and the local waste incineration CHP plant *Reno Nord*, accounting for 56% and 23% in 2016, respectively. The small separate DH systems have a total heat demand incl. grid losses of 0.11 TWh/year [36].

Not all households in the municipality are connected to DH, and as such, besides the DH demands there is also a heating demand of about 0.31 TWh/year that is met by individual units. These are mainly biomass boilers, which account for 0.22 TWh/year [35].

In 2016, the total electricity demand in Aalborg Municipality was about 1.15 TWh. The electricity system is connected to the national electricity system of Denmark. Nordjyllandsværket is an extraction mode CHP plant with a condensing mode power capacity of 410 MW and a maximum heat delivery of 490 MJ/s. Apart from evidently not being RES-based, the plant is nearing the end of its technical lifetime and decommissioning is planned for 2028. Of the variable RES electricity sources in the municipality, onshore wind power produced a total of 246.5 GWh and photo voltaics (PV) produced 13 GWh in 2016 [37].

Besides these demands the transport sector used about 2.1 TWh fuels in 2016, with 1.1 TWh being diesel usage, 0.56 TWh being petrol use, and 0.43 TWh being fuel for aviation [35].

Fig. 2 shows the fuel usage by energy sector in Aalborg Municipality in 2016.

The energy system of Aalborg Municipality has previously been an objective of research, with a 100% renewable energy scenario, however, while DH played a significant role in the scenario, this work did not factor in potential benefits of lowering DH temperatures [26]. Likewise, Sacchi and Ramsheva [38] studied the potential for utilising industrial excess heat in the DH system of Aalborg, finding significant potentials. Their most ambitious scenario *"results in a tenfold lowering of the carbon footprint of the heat compared to the current scenario"*. However, this analysis was based on life-cycle assessment and economic potentials while temporal dynamic simulations of the energy systems were not included.

Mahbub et al. [39] used Aalborg as a case for testing scenario-reduction by genetic algorithms for developing optimal energy scenarios. Other analyses have tested different types of DH HPs for the integration of wind power [40] and the role of storage in the Aalborg energy system [41]. Čulig-Tokić et al. [42] compared DH systems in Aalborg and Zagreb, finding advantages in the Aalborg system in terms of metering system (flow rather than energy), water losses and temperature levels where *"Aalborg DH has far lower supply temperatures that translate into lower energy losses"*.

Bühler et al. [43] made a GIS analysis for all of Denmark in order to identify the utilisation potential for industrial excess heat in DH, and found for Aalborg that over 80% of the DH demand could be covered by excess heat. However, the analysis did not investigate different DH temperature levels.

3.2. Scenario generation and description

The analyses presented in this paper are based on work from the *Smart Energy Aalborg* vision from 2019 [44,45]. The goal of *Smart Energy Aalborg* is to show possibilities for an energy system based on 100% RES for Aalborg Municipality that fits into the overall Danish energy system in 2050, where the national Danish goal is to have an energy supply based on 100% RES. *Smart Energy Aalborg* has been developed in EnergyPLAN, where a reference model of the existing energy system has been created in order to validate the model. In *Smart Energy Aalborg*, scenarios are shown for how the energy demands can be met using only RES by implementing energy savings at end-users, expanding the central DH grid, increasing energy system flexibility, increasing the amount of variable RES, and changing energy conversion units. It is not the goal of this paper to detail the development of the scenario, as such, only

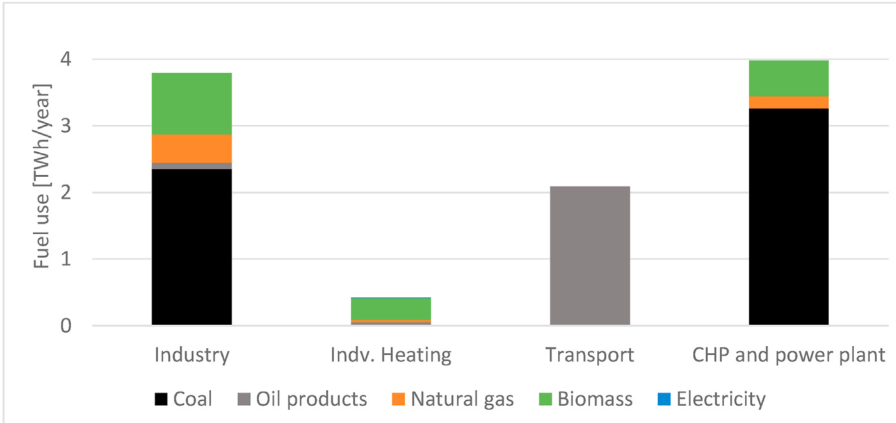

Fig. 2. Yearly fuel use by sector in Aalborg Municipality in 2016. Based on data from Ref. [35].

the overall principles are described here. To go for 100% RES, the following has been done in the energy system:

- The wind power and PV capacities, and consequently their production, have been increased significantly.
- The industrial and transport demands are changed to be supplied by direct electrification, biomass, and liquid and gaseous electrofuels, that are produced locally using electrolysers alongside a carbon source. The carbon sources utilised are CO_2 from e.g. biogas production and biomass.
- Part of the individual heating demand is changed to be connected to the DH systems, and the remaining individual heating is supplied by individual HPs in each household.
- In the central DH system, the existing extraction mode CHP plant is scrapped and replaced by a simple cycle gas turbine, HPs, electric boilers, flat plate solar thermal collectors, and increased utilisation of excess heat from industries and electrolysers. The waste incineration CHP is kept in operation, as it is expected that even with increased recycling and use of some biodegradable waste for biogas production there will still be a waste reminder that has to be handled. Due to the increased excess heat utilisation in the central DH system, seasonal pit thermal storage with a combined capacity of 40 GWh is also installed. It is assumed that the existing aboveground short-term sensible heat storage capacity of 1.58 GWh is maintained with an increased cost, as described in section 3.3. This capacity is installed to achieve the lowest total annual costs for the energy system.
- In the separate DH systems that are not connected to the main contiguous DH grid, flat-plate solar thermal and HPs are added alongside existing CHP gas engines and fuel boilers. The existing aboveground short-term sensible heat storage capacity of 0.13 GWh is also kept in the systems.

100% RES energy system scenarios have been developed for both 3GDH and 4GDH systems. The exact capacities are different for these two cases. The scenario used is the so-called *balanced scenario* with increased hydrogen production from Ref. [44], which is the main scenario also described in Ref. [45]. In this scenario, import and export of electricity and gas to and from the energy system of Aalborg Municipality are possible using the national electricity and gas systems, though the yearly net import of electricity and gas is zero. The scenario has been developed and modelled using EnergyPLAN, and as such, the balancing is based on hourly production and consumption. Furthermore, it has been developed based on the following principles:

- All primary energy consumption must be based on 100% RES.
- Biomass consumption must not exceed 1.71 TWh/year − corresponding to the biomass potential in Aalborg Municipality [26].
- The gross import of electricity must not exceed 50 GWh/year. This is a very modest level compared to the main scenarios electricity production of 3.11 TWh, and is used as a guideline for making sure that the energy system of Aalborg Municipality does not export large electricity system fluctuations that would need to be handled in other areas.
- The yearly net import of gas must be zero, where the production of gaseous electrofuels in the energy system of Aalborg Municipality is used to ensure this balance.

Further details of the scenarios are found in Ref. [44,45]. The EnergyPLAN models and used distributions can be found at [46].

In this paper, the focus is on the differences between the 3GDH and 4GDH, and as such, these differences are shown in more detail hereafter.

3.3. Effects of 4GDH at the district heating plants

Due to the reduced forward temperature, return temperature and the lower temperature difference between forward and return, changing from 3GDH to 4GDH will affect the production and heat storage technologies at the connected DH plants. As shown in Lund et al. [10], transitioning from 3GDH to 4GDH is expected to increase the COP of HPs and the thermal efficiency of CHP units including waste incineration. This work also found that condensing boilers will see improvements in efficiency, however, this is excluded from this analysis as the fuel boilers in this scenario only account for about 1% of the total DH production. Lund et al. [10] also found that going from 3GDH to 4GDH will decrease the investment cost of solar thermal per MWh produced and increase the investment cost of thermal storages per MWh capacity.

The scenario makes extensive use of HPs where the COP within a temperature range can be assumed linearly dependent on the Carnot efficiency. Based on Swedish experience from Fortum, a system efficiency (defined as the ratio between the actual COP and the Carnot efficiency) of 64% is applied. This is based on a HP condenser temperature of 70 °C, and an evaporator temperature of 5 °C giving a Carnot factor of 5.28, where the measured COP is 3.4. With 3GDH temperature levels of 80 °C/45 °C the resulting COP is

2.9 but decreasing temperature levels to 55 °C/25 °C increases this by a third to 3.9. In both cases, the condenser temperature is assumed 5K above the DH forward temperature to provide a reasonable heat exchanger ΔT. Also, the evaporator temperature is assumed being 5 °C, which is about 5K below the average seawater temperature in Denmark and thus an appropriate level for extracting heat out of this low-temperature heat source.

As described in Section 3.2, in the main scenario for Aalborg Municipality three types of CHP units are utilised. The CHP units in the central DH system are a simple cycle gas turbine and steam-based waste incineration CHP, which operate separately of each other, as is the case currently with the existing waste incineration plant and central coal-fired CHP plant. For both, the characteristics are based on [47], where the efficiency of the simple cycle gas turbine is listed with one value for within the generating capacity range if of 40–125 MW_e – thus with no size dependency. Equally so for the waste incineration based on a 42 MW waste feed with the produced steam being used in a steam turbine to produce electricity and heat. Here [47] lists a slight size-dependency with separate values for feed in of 35, 80 and 220 MW, however, as no change in sizes is considered here, size dependency is not considered.

The simple cycle gas turbine is modelled having an electric efficiency of 44% and a thermal efficiency of 55% in the 4GDH situation, where the electric efficiency is expected to remain unchanged between 3GDH and 4GDH, however, the further the temperature of the gas turbine exhaust gasses can be lowered with low DH temperatures, the better the heat recovery in line with data from Refs. [48]. Thus, the thermal efficiency is modelled 2%-points lower with 3GDH temperature levels than with 4GDH levels. For the waste incineration CHP, the efficiencies at 4GDH is expected to be 25% electric and 76% thermal, where again it is expected that the change to 4GDH mainly affects the thermal efficiency. This is expected being around 10%-point lower at 3GDH based on data from Frederiksen and Werner [5].

In the smaller separate DH areas gas engines are used for CHP production with an electric efficiency of 39% and a thermal efficiency of 55% at the 4GDH temperature levels. These efficiencies are based on the current yearly average efficiencies, as part of the scenario is to keep the existing gas engines. Thus, any size dependency of the efficiency is not important here. Again, the electric efficiency is expected to remain unchanged between 3GDH and 4GDH temperature levels, however, the thermal efficiency is expected to be 5%-points lower at the 3GDH temperature levels, as 4GDH levels enable a better extracting of heat from the various sources of the engine - water cooling, oil cooling and exhaust gas cooling.

For very low engine cooling water temperatures, there is the theoretical possibility of too good cooling that while affecting heat uptake positively could also affect electric efficiency, however, the return water temperature in these cases is not at such low levels. Even if so, shunting as in e.g. marine engines would not permit this. This naturally also limits the heat efficiency. Data from Refs. [48] indicate steadily increasing heating uptake down to at least temperatures of 20 °C, however, below an intercooler temperature of 40 °C (for natural gas engines), condensation becomes an issues, which also sets a limit [49]. This is even higher with biogas engines where the humidity in the fuel is higher.

For gas turbines, cooling of inlet is even applied in warm climates, and again, data from Ref. [48] demonstrate increased heat uptake for exhaust gas well below the levels applied in this article. For temperatures around 38 °C the effect is noticeable and depending on application this can simply be through condensation or through the use of exhaust gas cooling using an absorption heat pump [48].

For flat-plate solar thermal and the sensible heat storages the cost estimates for 3GDH and 4GDH from Ref. [10] is used, as the heat storage and solar thermal technologies listed there are the same as those used in this work. As such, the cost for solar thermal is 544 EUR/MWh at 3GDH levels and 382 EUR/MWh at 4GDH levels, based on a fixed cost per m^2 collector and increased efficiency at lower temperatures. The sensible heat storages are assumed stratified with the temperature in the top being equal to the forward temperature in the DH system and the temperature in the bottom being equal to the return temperature. As such, based on a fix cost per volume of storage and energy content per volume of storage being proportional to ΔT, the cost for heat storages is 3.17 M EUR/GWh at 3GDH levels and 3.7 M EUR/GWh at 4GDH levels.

Table 1 shows the overview of the found differences of going from 3GDH to 4GDH.

3.4. Grid benefits of 4GDH

DH grid losses are modelled separately in two groups; one group with the large–scale contiguous DH system covering the main city and more, and a group with the separate small-scale DH systems placed farther afield from the central system.

Losses at current temperature levels are known with 27% in the small-scale systems and 21% in the large-scale system. These losses are converted to a loss per degree temperature difference between DH pipe water and the surrounding soil as shown in Eqs. (1)–(4).

$$\mathrm{Loss}_{\mathrm{DH}} = \mathrm{Loss}_{\mathrm{Forward}} + \mathrm{Loss}_{\mathrm{Return}} \tag{Eq.1}$$

$$= k^*\Delta T_{\mathrm{Forward}} + k^*\Delta T_{\mathrm{Return}} \tag{Eq.2}$$

$$= k^*\left(T_{\mathrm{Forward}} - T_{\mathrm{Drop}}/2 - T_{\mathrm{Soil}}\right) + k^*\left(T_{\mathrm{Return}} - T_{\mathrm{Drop}}/2 - T_{\mathrm{Soil}}\right) \tag{Eq.3}$$

$$= k^*\left(T_{\mathrm{Forward}} + T_{\mathrm{Return}} - T_{\mathrm{Drop}} - 2T_{\mathrm{Soil}}\right) \tag{Eq.4}$$

Where ΔT is the temperature difference between a) the soil and b) the water average temperature between heat producer and consumer, and T_{Drop} is the drop in temperature from producer to consumer.

For a given system, k is a constant factoring in pipe surface area, insulation property and length, and may be determined based solely on temperature levels and know losses. For these analyses, k is also constant across the analyses as there are no changes to the pipes or grid layouts.

In the assessment, it is assumed that the temperature drops 4K along both the forward and the return pipe – and that the soil temperature is a constant 8 °C; a design temperature used in Denmark [50]. Losses at other temperature levels are based on the 3GDH baseline loss and the temperature difference – corresponding to using the same pipes with the same insulation properties. With the temperatures applied here, this gives 4GDH losses of 18.6% in the small-scale systems and 14.5% in the large-scale

Table 1
Differences for technologies at the DH plant of going from 3GDH to 4GDH.

Technology	COP	Thermal efficiency	Investment cost
HP	+1.0	–	–
Simple cycle gas turbine	–	+2%-points	–
Waste incineration	–	+10%-points	–
Gas engines	–	+5%-points	–
Solar thermal	–	–	−162 EUR/MWh
Heat storage	–	–	+0.53 M EUR/GWh

system at current heat demands.

Relative heat losses in DH grids are also susceptible to heat savings at the end-user, as grid losses in absolute terms generally will remain the same. Thus, with losses being related to the temperature difference and not related to flows, this provides for a constant DH grid loss in absolute terms irrespective of savings. The scenario is based on 30% heat savings which causes the relative DH loss to increase to 27% in the central DH system in the 3GDH case.

3.5. Excess heat potential

The industrial excess heat potential has mainly been identified by contact with local stakeholders, Aalborg Portland and the utility company Aalborg Forsyning, alongside contact with the largest retailer of consumer goods in Denmark, COOP Denmark.

Aalborg Portland produces both white and grey cement, and the current utilised excess heat source originate solely from the production of white cement. The primary source of waste heat is from water condensation as the cement burning process is a wet process. The limestone is wet when excavated and further water is injected to create a sufficiently fluid slurry. The hot water vapours are condensed in a heat exchanger heating up DH water. Aalborg Portland has identified more technically possible excess heat sources that could be utilised in the DH system if the temperature requirements for them were lowered to 4GDH levels. The new potential sources at Aalborg Portland can be seen in Table 2, where a lifetime of 20 years is assumed for annualising the investment costs. The costs are also estimated by Aalborg Portland. These potentials may be compared to the 2016 heat recovery of 327 GWh.

The HP to reduce the return temperature at Aalborg Portland is expected to have a COP of 8 at 4GDH temperature levels. The annualised costs are excluding purchase of electricity for operating the HP. This electricity demand is included in the scenarios.

Aalborg Forsyning is the local DH supplier, which previously has investigated potential excess heat sources in other industries than Aalborg Portland. Aalborg Forsyning has not identified any potential heat sources that, like Aalborg Portland, can be used directly in the DH system, even at 4GDH temperature levels. As such, all potentials in other industries include the use of HPs to boost the temperature to match the forward temperature in the DH system. The sources that Aalborg Forsyning have identified are shown in Table 3. All sources, except the category “Other industries” shown in Table 3, can be utilised in both 3GDH and 4GDH systems but with a different COP for the HP operation. The heat potentials are including the electricity consumption of the heat pumps. The annualised costs are excluding purchase of electricity for operating the HPs.

Besides these two, the excess heat potential from supermarkets’ refrigeration systems has been assessed. This has been evaluated based on phone interview with Technical consultant at COOP Denmark, Bendt Dahl, regarding COOP Denmark’s experiences with recoverable amounts of excess heat from refrigeration in their stores, which was assumed to be representative also for similarly-sized supermarkets in other supermarket chains.

Three different categories were established based on the normal size of supermarkets in that chain, where Category 1 is assumed to be able to provide 75 MWh/year/store, Category 2 able to provide 100 MWh/year/store, and Category 3 is assumed able to deliver 150 MWh/year/store. These potentials will first be used in the individual stores and any excess can be delivered to the DH grid. However, in this it is all categorized as excess heat, as the energy system impact is the same regardless of whether the internal used energy is counted as reduced DH demand or as excess heat delivered to the DH grid. The excess heat is assumed to be delivered to the grid at 65 °C, despite this it is assumed to be usable in the 3GDH scenario, due to it mostly being available for DH in the summer period where the requirements to the forward temperature generally are lower, its geographical dispersion meaning it is closer to the end-user, and the relative low energy potential per store. The list of included supermarket chains is shown in Table 4 based on the assumed category.

Using the list in Table 4 and the websites of the supermarket chains, the number of potential stores in each category within the area of the expanded DH grid in Aalborg Municipality was found. The websites were all accessed the 21st of August 2018, and a total of 94 stores were found to be relevant, with 72 in Category 3, 14 in Category 2, and 8 in Category 1. This results in a total technical excess heat potential from supermarkets in the 3GDH scenario of 8 GWh/year. The exact effect of reducing the DH temperatures to 4GDH levels is not known, however, it expected that the utilisation would increase, due to the reduced DH return temperature. As such, it is simply assumed that the potential excess heat is proportional to the difference between the temperature of the excess heat source and the return temperature of 3GDH and 4GDH, respectively. With an excess heat temperature of 65 °C, this difference is 25 °C for 3GDH and 45 °C for 4GDH, meaning that the potential is increased by 60% in 4GDH compared with 3GDH. As such, the excess heat potential from supermarkets is assumed to be 12.8 GWh/year in the 4GDH scenario.

Summing up the excess heat potentials, the uptake of excess heat from industrial processes is found to be increased from 335 GWh direct and 113 GWh indirect via HPs with 3GDH to 683 GWh direct and 168 GWh indirect with 4GDH.

4. Results

Though the energy system model is holistic and includes all energy sectors, the results presented in this section focus on the DH system and electricity sector as these are directly affected by the change from 3GDH to 4GDH. However, when refering to the energy system then it is the entire modelled energy system, and not only DH and electricity. This thus includes industrial fuel uses, individual heating and transport.

The analyses do not address any particular transaction costs for the transition, but exclusively address the total annual costs - i.e. annualised investment costs, operation and maintenance, and fuel costs for all sectors of the energy system.

Table 2
Technical potential new excess energy sources at Aalborg Portland in 4GDH.

Excess heat source	Heat potential [GWh]	Annualised cost [M EUR]
Increased output from existing units in 4GDH	139	–
Optimisation of existing units	108	0.73
Heat recovery from grey cement kiln	97	0.73
HP reducing return temperature to existing units	34	0.48
Total	**378**	**1.94**

Table 3
Technical potential excess heat sources in other industries than Aalborg Portland.

Excess heat source	Heat potential [GWh]	Annualised cost [M EUR]	COP in 3GDH	COP in 4GDH
Arla Foods Akafa	12	0.11	4.2	6.6
Wastewater treatment plants	98	1.17	3	4
Industries at the commercial harbour	3	0.03	4.3	6.8
Other industries	21	0.22	–	6.1
Total	**134**	**1.53**		

Table 4
Supermarket chains included in the assessment based on category.

Category 1	Category 2	Category 3
Bilka, Føtex, Kvickly, Salling	Meny, SuperBrugsen	ALDI, Dagli'Brugsen, Fakta, Lidl, Netto, Min Købmand, Rema 1000, SPAR

4.1. Annuals costs and energy balance in the main scenarios

The total annual costs –- for the energy system is 624 M EUR in the 4GDH scenario and 641 M EUR in the 3GDH scenario. The reduction in energy system costs comes from reduced investments in energy producing units, which in turn also reduces the fixed operation and maintance costs, as the 4GDH energy system can supply the demands with lower capacities.

The 4GDH scenario has 30 MW_e less CHP, 131 MW_{th} less HP, 24 MW_e less electrolysers, 7 MW_e less PV, and 62 MW_e less wind power, but 45 MW_{th} more excess heat capacity and 4 MW_{th} more waste incineration capacity, due to increased utilisation potential of industrial excess heat and increased thermal efficiency of the waste incineration. The reduced wind power capacity is due to the reduced electricity need for the HP in the DH system. In total, the 4GDH scenario has 246 M EUR less investment costs, corresponding to a reduction in the annual costs of 13 M EUR. The lower capacity also results in lower fixed operation and maintance costs corresponding to 3 M EUR/year.

The total primary energy consumption for the entire energy system (all energy sectors) for each of the two scenarios are shown in Fig. 3.

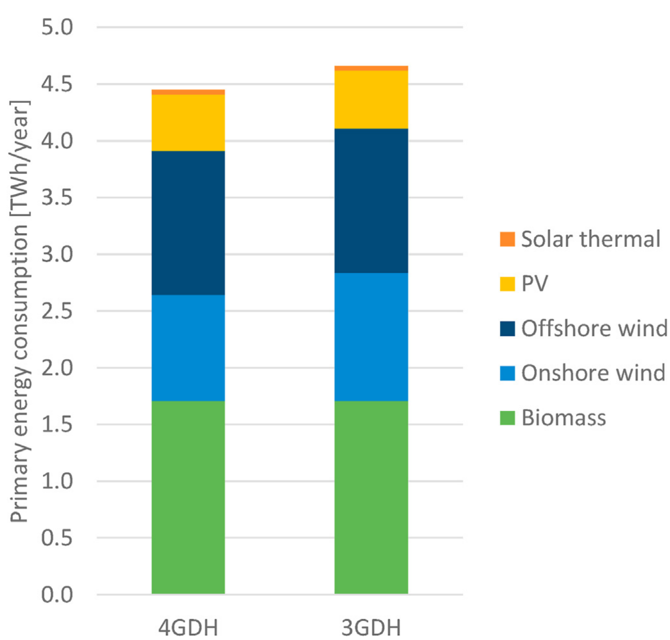

Fig. 3. Yearly total primary energy consumption for all sectors in the 4GDH and 3GDH scenarios for Aalborg Municipality.

As shown in Fig. 3, going from 3GDH to 4GDH reduces the total primary energy consumption of all energy sectors in Aalborg Municipality from 4.66 TWh/year to 4.45 TWh/year, corresponding to a decrease of 4.5%.

Fig. 4 shows the DH production by technology for the two scenarios. The Balance category is energy that is produced but not utilised due to temporal differences between production and consumption of DH, despite the inclusion of heat storage systems.

From Fig. 4, it can be seen that the DH demand in the 4GDH scenario is 1.56 TWh, and in the 3GDH scenario it is 1.82 TWh, with the difference being a lower grid loss in the 4GDH scenario. Likewise, a major difference between the two scenarios is the excess heat from industries, where it is estimated that 0.4 TWh more industrial excess heat can be utilised in the 4GDH scenario, compared with the 3GDH scenario. There is also 0.17 TWh excess heat from the production of electrofuels; however, this excess heat is assumed to be unaffected by the change in DH temperatures. The increase in excess heat from industries in the 4GDH scenario, alongside the reduced grid loss, results in that 0.18 TWh of the heat produced in the DH system in the 4GDH cannot be utilised. This lost heat is produced in the summer months, where the DH demand is low due to low space heating demands, while excess heat production is assumed to be constant in absolute terms through the simulated year. The lower excess heat potential in the 3GDH

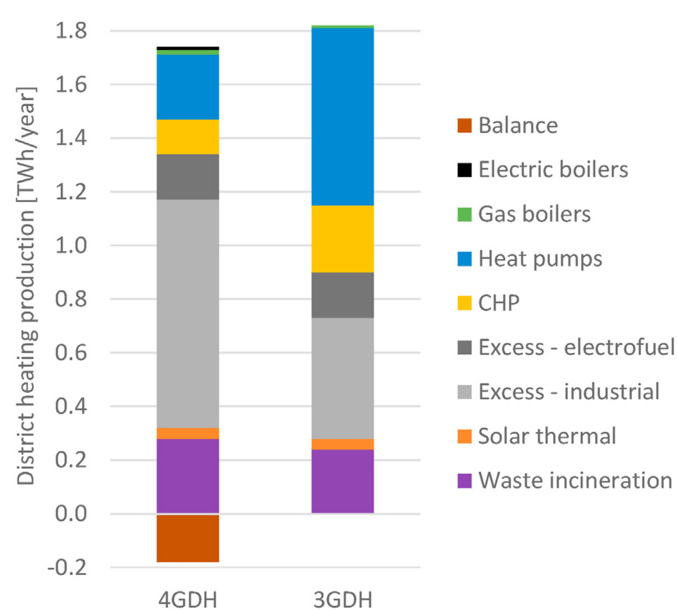

Fig. 4. Yearly DH production by technology sectors in the 4GDH and 3GDH scenarios.

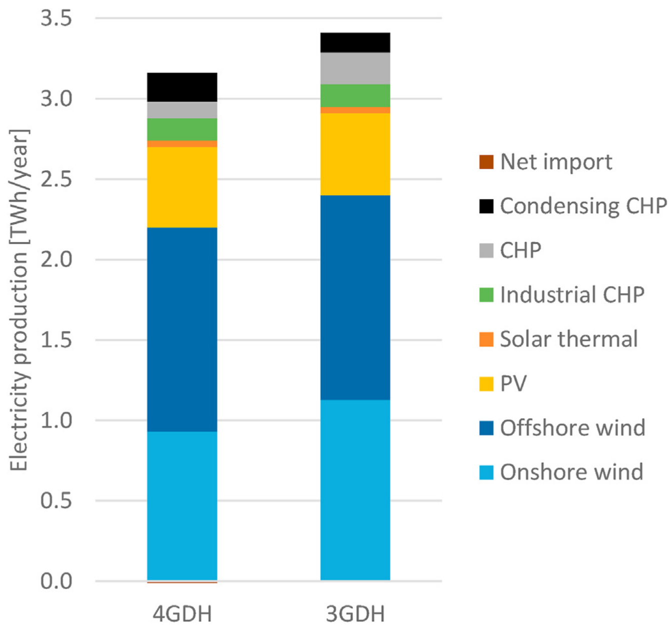

Fig. 5. Yearly electricity production by production technology in the 4GDH and 3GDH scenarios.

scenario results in higher utilisation of the HP and CHP, compared with the 4GDH scenario.

As seen in Fig. 5, the electricity production in both scenarios is based on variable RES, with wind power accounting for 81–82% of the variable RES electricity production and PV accounting for the remainder. The yearly net import of electricity is zero in the 3GDH scenario and 0.01 TWh in the 4GDH scenario. The total electricity production including net import in the 4GDH scenario is 3.11 TWh and in the 3GDH scenario it is 3.37 TWh.

The higher electricity production in the 3GDH scenario is due to a higher electricity consumption because of the higher utilisation of DH HPs with a lower COP. The DH HPs use 0.17 TWh more electricity in the 3GDH scenario than in the 4GDH scenario. As all gas for the CHP units are produced in the energy system, as described in Section 3.2, the increased use of the CHP units in the 3GDH scenario also results in an increased electricity consumption for gas production of 0.1 TWh, which is mainly used in the electrolysers. The remaining difference between the two is that the 4GDH scenario has a higher electricity usage of 0.01 TWh for the DH electric boilers.

4.2. Sensitivity analyses

In this section each of the differences between 4GDH and 3GDH are analysed in more detail, to quantify their individual effect. The effect of each of these improvements is analysed by changing one at a time in the 4GDH scenario from the 4GDH level to the 3GDH level. The effect on the solar thermal and heat storages only affect the total annual costs of the energy system, but the remaining changes also result in a changed energy production of the scenario.

To adhere to the scenario restrictions described in Section 3.2, the scenario is balanced by adjusting the capacity of onshore wind power, PV, DH HP, and CHP to ensure that each scenario adheres to these restrictions. These adjustments have been done through iterations. In case of needing more primary energy, the priority has been given to increasing the onshore wind power capacity due to it having the lowest electricity producing cost. As shown in Fig. 3, electricity from RES is the only other primary energy source besides biomass, which is limited. Increasing the production from onshore wind power will result in increased CEEP, as well as increased production on DH HP, DH electric boilers and the electrofuel technologies, which will affect the electricity and gas balance. As such, the PV, DH HP and CHP capacities are also adjusted to ensure the balance of these, as adjusting the onshore wind power capacity only is not always sufficient to ensure the scenario restrictions are adhered to. The changes made do not constitute the only possible changes that can be made to adhere to the scenario restrictions, nor is it guaranteed to be the lowest cost solutions, as such, they merely present possible adjustments. In the following tables, the MW_e for onshore wind power, PV and CHP are changes in the installed production capacities, and for DH HP it is the installed capacity in electricity consumption. The resulting adjustments made to capacities for the sensitivities are found in Table 5.

With these adjustments to the 4GDH scenario the changes to primary energy consumption and total annual costs shown in Table 6 are found.

As seen in Table 6, decreasing the excess heat potential to 3GDH level has the largest impact on both primary energy consumption and total annual costs, which in both cases are higher than the full 4GDH scenario. The reduction of excess heat of 0.4 TWh/year results in an increase of CHP heat production of 0.06 TWh, increase of HP production of 0.1 TWh, increase of electric boiler production of 0.05 TWh, and increased production by fuel boilers of 0.02 TWh. The remaining 0.16 TWh is not produced by other units, as this amount was non-useable in the DH system.

Increasing the grid loss to 3GDH level has the second largest impact on the primary energy supply but has a similar impact on the total annual costs as 3GDH COP for the DH HP. Increasing the grid loss to 3GDH level increases the total DH demand incl. grid loss by 0.26 TWh/year where the extra DH production originates from CHP (0.03 TWh), HP (0.09 TWh), electric boilers (0.05 TWh), and the fuel boilers (0.03 TWh). The remaining 0.06 TWh is from being able to utilise otherwise non-usable excess heat, especially in the summer months.

A reduced CHP efficiency only increases the primary energy consumption with 0.02 TWh/year and the total annual costs by 1 M EUR. The effect of 3GDH CHP efficiencies is most evident for the waste incineration as this produces 0.04 TWh/year less DH, which instead is met by the HP and fuel boilers producing 0.01 TWh/year each, and the remaining 0.02 TWh is not produced by other units, as this amount were non-useable in the DH system.

The flexible gas engines and simple cycle gas turbine do not see a change in their yearly DH production, as the reduced thermal efficiency simply results in less condensing CHP operation as the DH production can be utilised in more hours of the year, and as such, CHP operation sees an increase in electricity production of 0.01 TWh/year with a corresponding reduction in condensing CHP operation of 0.01 TWh/year.

The reduced HP COP only has a marginal effect on the system, and in the energy balance it only results in an increase in the electricity demand of 0.02 TWh.

As described in Section 3.3, the solar thermal and heat storage only affect the total annual costs of the energy system. 4GDH temperature level increases the total costs of the heat storages in the scenario with about 0.05 M EUR/year. The heat storage capacity is 1.705 GWh. The 4GDH temperature level decreases the total cost of the solar thermal in the scenario with about 0.4 M EUR/year. The solar thermal has a total capacity of 0.05 TWh/year.

As the decrease in excess heat seems to be the largest benefit for the modelled energy system, it is relevant to analyse the effect of the largest excess heat source, Aalborg Portland. As such, a scenario is created where the excess heat from Aalborg Portland is removed. In order to adhere to the scenario restrictions in the 4GDH scenario,

Table 5
Capacity adjustments for balancing the sensitivity analysis scenarios.

[MW$_e$]	Increased grid loss	Reduced HP COP	Decreased excess heat utilisation	Reduced CHP efficiency
Onshore wind power	+30.5	+8	+41	+5
PV	–	–	+7	–
DH HP	–	+9	–	–
CHP	–	–	+20	–

Table 6
Result of sensitivity analyses shown alongside the full 4GDH scenario for comparison.

	4GDH	Increased grid loss	Reduced HP COP	Decreased excess heat utilisation	Reduced CHP efficiency
Primary energy consumption [TWh]	*4.45*	4.55	4.48	4.6	4.47
Total annual costs [M EUR]	*624*	627	627	630	625

the CHP capacity is increased by 20 MW$_e$, onshore wind power is increased by 30 MW, PV is increased by 42 MW, and the DH HP is increased by 34 MW$_e$ compared with the original 4GDH scenario. The removed excess heat from Aalborg Portland is then replaced by 0.13 TWh heat from CHP, 0.41 TWh HP, and the 0.18 TWh surplus production of DH is removed, as the summer production of excess heat is now below the summer DH demand. Due to the increased capacities for CHP and HP, the DH production on the fuel boilers is reduced by 0.01 TWh, as is the DH production on the electric boilers. For comparison a version of the 3GDH scenario has also been created. Here the wind power capacity is increased by 34 MW and the DH HP is increased by 63 MW$_e$ compared with the original 3GDH scenario. Here the removed excess heat from Aalborg Portland is replaced by 0.27 TWh from DH HP and 0.06 from CHP. For the 4GDH removing the excess heat from Aalborg Portland increases the primary energy consumption by 0.15 TWh and the total annual costs by 12 M EUR, where in the 3GDH the primary energy consumption is increased by 0.11 TWh and the total annual costs by 15 M EUR. As such, when not including the excess heat from Aalborg Portland in the scenarios, the advantage of going from 3GDH to 4GDH changes, with a decrease in primary energy consumption of 3.6% and a decrease in total annual costs of 3%, compared with the original 4.5% and 2.7%, respectively.

Again, the four 4GDH benefits are analysed separately compared with the full 4GDH scenario. The resulting adjustments made to capacities for the four sensitivities can be found in Table 7.

With these adjustments, the changes to primary energy consumption and total annual costs shown in Table 8 are found.

As shown in Table 8, without excess heat production from Aalborg Portland, the 3GDH effect on the excess heat potential has nearly no effect on the energy system. Increasing the grid loss to 3GDH level shows similar tendencies as with Aalborg Portland included, with increased primary energy consumption and total annual costs. Reducing the CHP efficiency to 3GDH levels show less of an effect on the overall energy system without the excess heat from Aalborg Portland, though the difference is minor. The reduced HP COP, however, has a larger effect on the energy system without the excess heat from Aalborg Portland, as the HPs now have a more dominant role in the DH system producing around 42% of the DH as opposed to around 14% when the excess heat from Aalborg Portland was included.

5. Conclusion

In this paper, the energy system effects of going from a 3GDH system to a 4GDH system in a RES-based energy system is investigated for the specific case of Aalborg Municipality, Denmark. The analyses indicate for the specific case that the uptake of excess heat from industrial processes can be increased from 335 GWh directly and 113 GWh indirectly via HPs with 3GDH to 683 GWh directly and 168 GWh indirectly with 4GDH, where the indirect use requires temperature boosting through HPs.

Grid losses can be reduced from 21% to 15%, not counting effects from energy savings in buildings. The COP of DH HPs can be increased from 2.9 to 3.9.

Altogether the total annual energy system costs is found decreased by around 2.7% from 641 M EUR in the 3GDH scenario to 624 M EUR in the 4GDH scenario, and the total primary energy consumption can be reduced by 4.5% going from 3GDH to 4GDH. A significant share of the industrial excess heat in the case origins from one company, where removing the industrial excess heat from this company reduces the share of industrial excess heat from 25% to 7% in the 3GDH scenario and from 55% to 9% in the 4GDH scenario, compared with the total district heating demand. Without this one company's industrial excess heat the reduction in total annual cost was found to be 3% and primary energy consumption was reduced by 3.6%, indicating that the effect of a large potential for utilisation of industrial excess heat especially effects the reduction in primary energy consumption. It was found that these benefits were especially due to the increased utilisation of excess heat from industrial processes and the benefits from a decreased grid loss.

The increased COP of the DH HP only showed minor benefits for the overall energy system. However, this was found to be related to

Table 7
Capacity adjustments for balancing the sensitivity analysis scenarios without excess heat from Aalborg Portland.

[MW$_e$]	Increased grid loss	Reduced HP COP	Decreased excess heat utilisation	Reduced CHP efficiency
Onshore wind power	+25	+20	+2	+3
PV	–	–	–	–
DH HP	–	+7	–	–
CHP	–	–	–	–

Table 8
Result of sensitivity analyses shown alongside the full 4GDH scenario for comparison without excess heat from Aalborg Portland.

	4GDH	Increased grid loss	Reduced HP COP	Decreased excess heat utilisation	Reduced CHP efficiency
Primary energy consumption [TWh]	*4.60*	4.68	4.66	4.60	4.61
Total annual costs [M EUR]	*636*	638	639	636	636

the relatively large amount of industrial excess heat, as with significantly less industrial excess heat the benefits of increased COP were larger. The changes in CHP efficiency as well as the cost of solar thermal and heat storages were found to only have minor effects on the overall energy system.

Author contribution statement

Peter Sorknæs: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. Poul Alberg Østergaard: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft. Jakob Zinck Thellufsen: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Review & Editing. Henrik Lund: Conceptualization, Methodology, Investigation, Data Curation, Writing - Review & Editing. Steffen Nielsen: Conceptualization, Investigation, Writing - Review & Editing. Søren Djørup: Investigation, Writing - Review & Editing. Karl Sperling: Investigation, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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